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Yakymyshyn et al.

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(54) **SIGNAL ACQUISITION PROBING SYSTEM USING A MICRO-CAVITY LASER CAPABLE OF SENSING DC VOLTAGES**

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G01R 31/26 (2006.01)

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See application file for complete search history.

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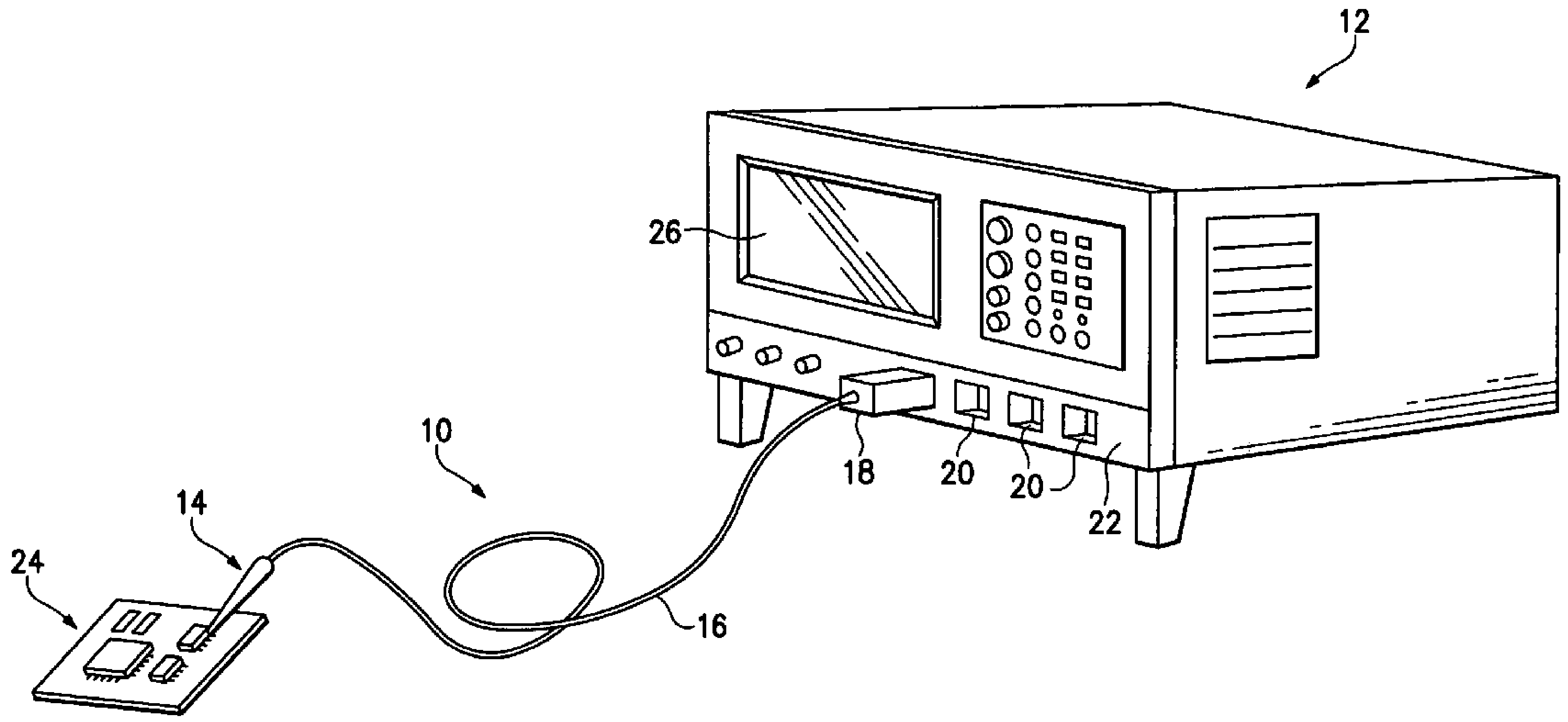
(57) **ABSTRACT**

A signal acquisition probing system uses a micro-cavity laser to acquire an electrical signal from a device under test. The micro-cavity laser has VCSEL gain mediums and an electro-optic optical resonant cavity. The micro-cavity laser is pumped by an external laser source and generates polarized frequency modulated optical signals derived from the device under test electrical signal creating an electro-magnetic field distribution in electro-optic material in the micro-cavity laser that overlaps the optical path of the polarized optical signals propagating in the electro-optic material. The polarized frequency modulated optical signals are coupled to an optical receiver which converts the polarized frequency modulated optical signals to an electrical signal. The electrical signal is coupled to measurement test instrument for processing and displaying of the electrical signal.

13 Claims, 6 Drawing Sheets



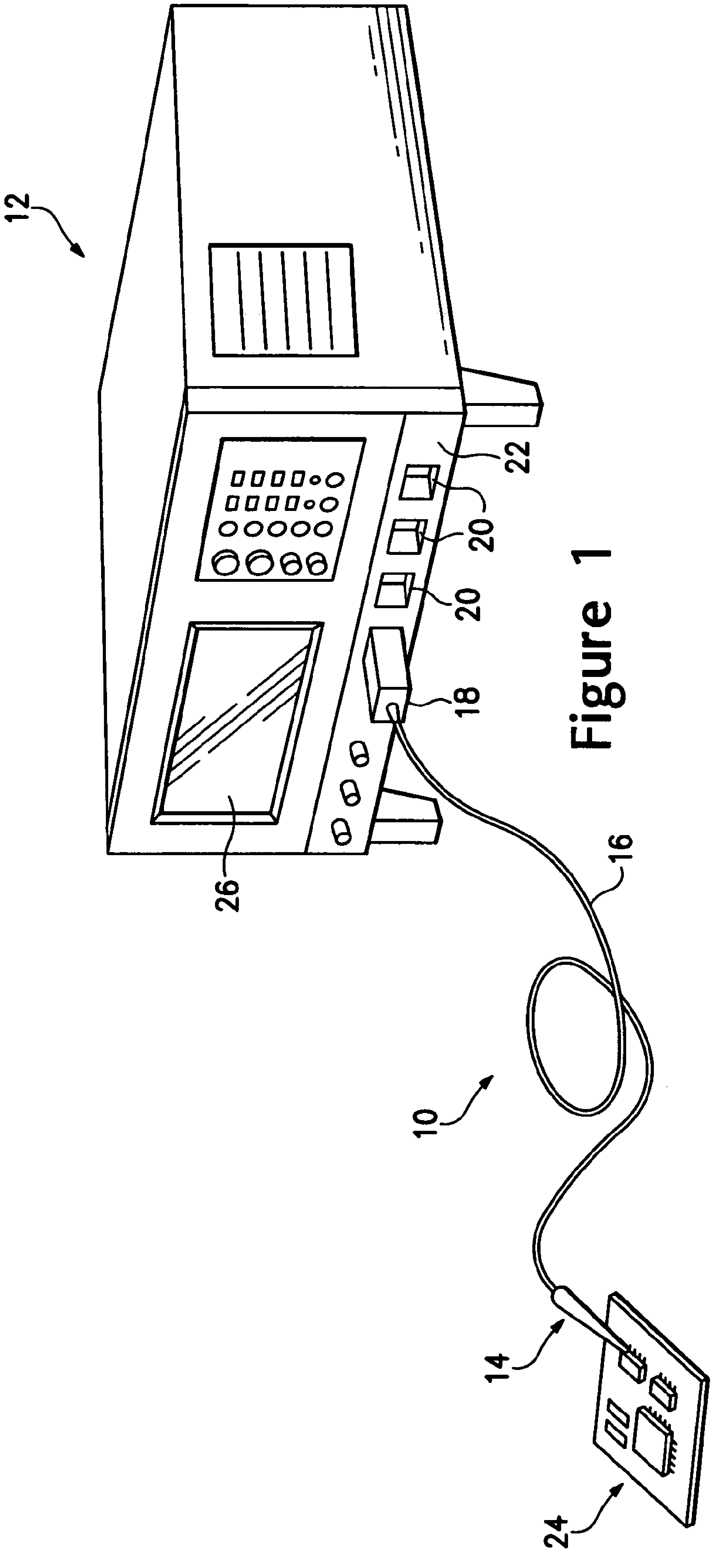


Figure 1

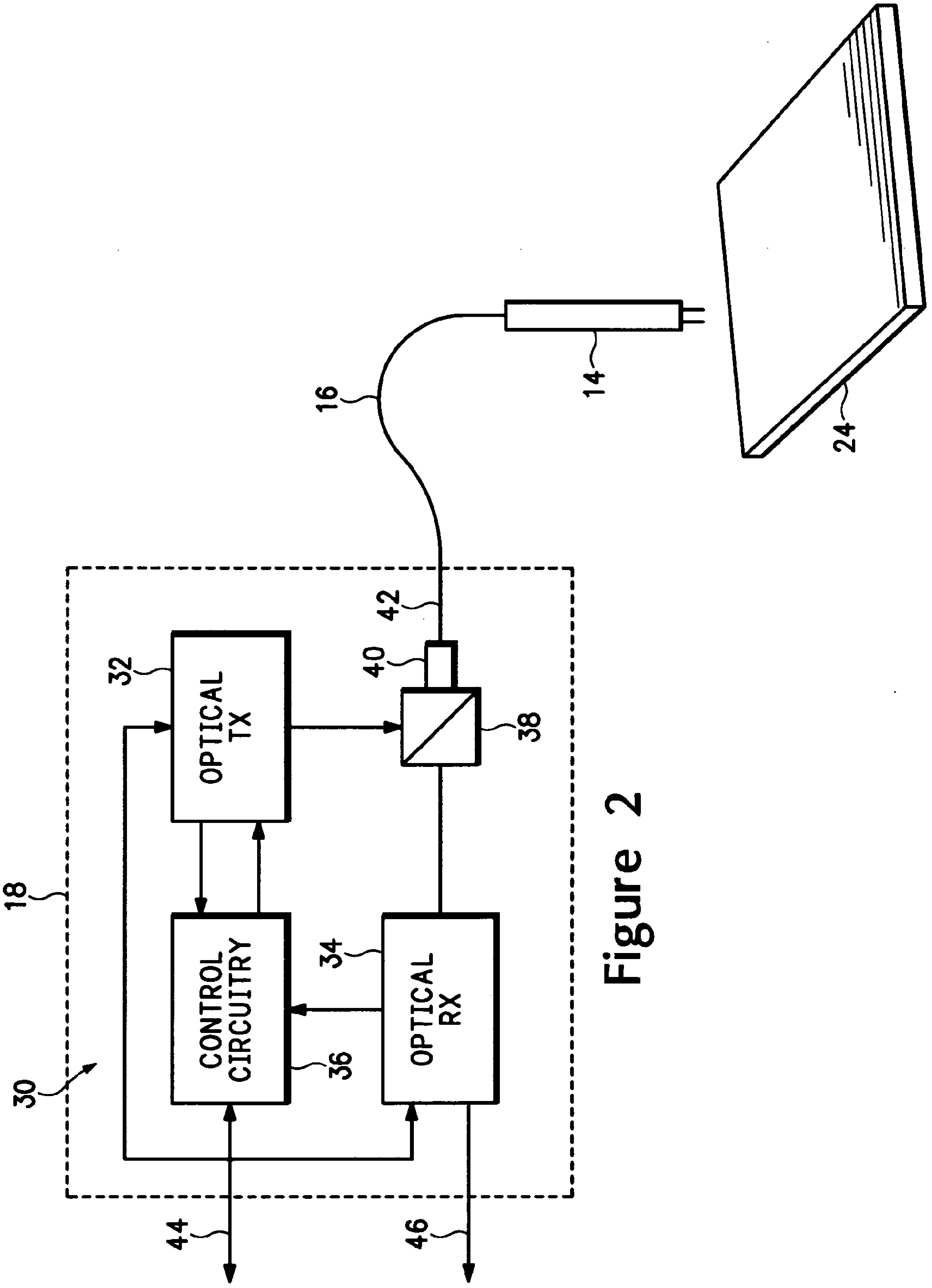

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Figure 2

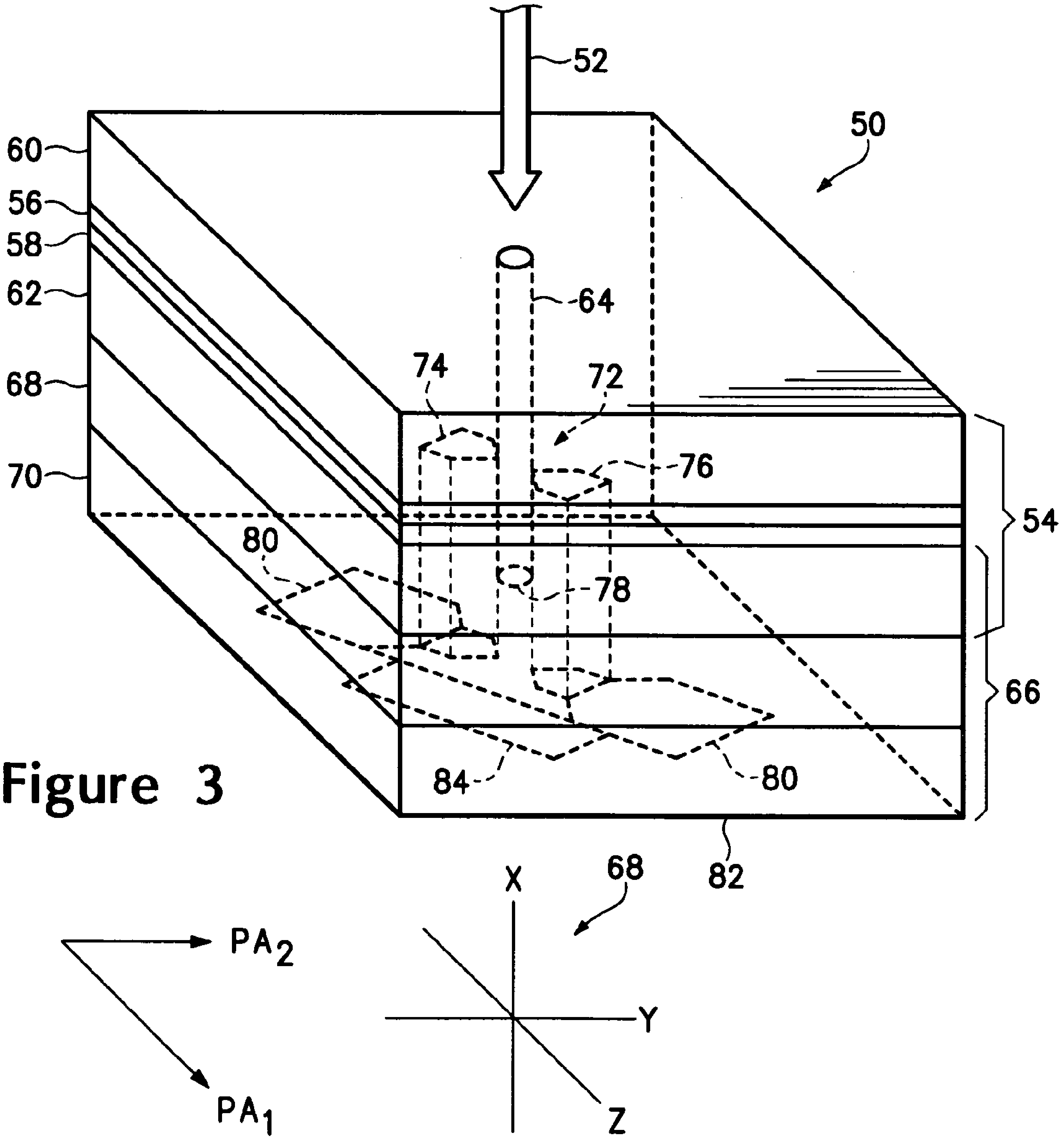

Figure 3

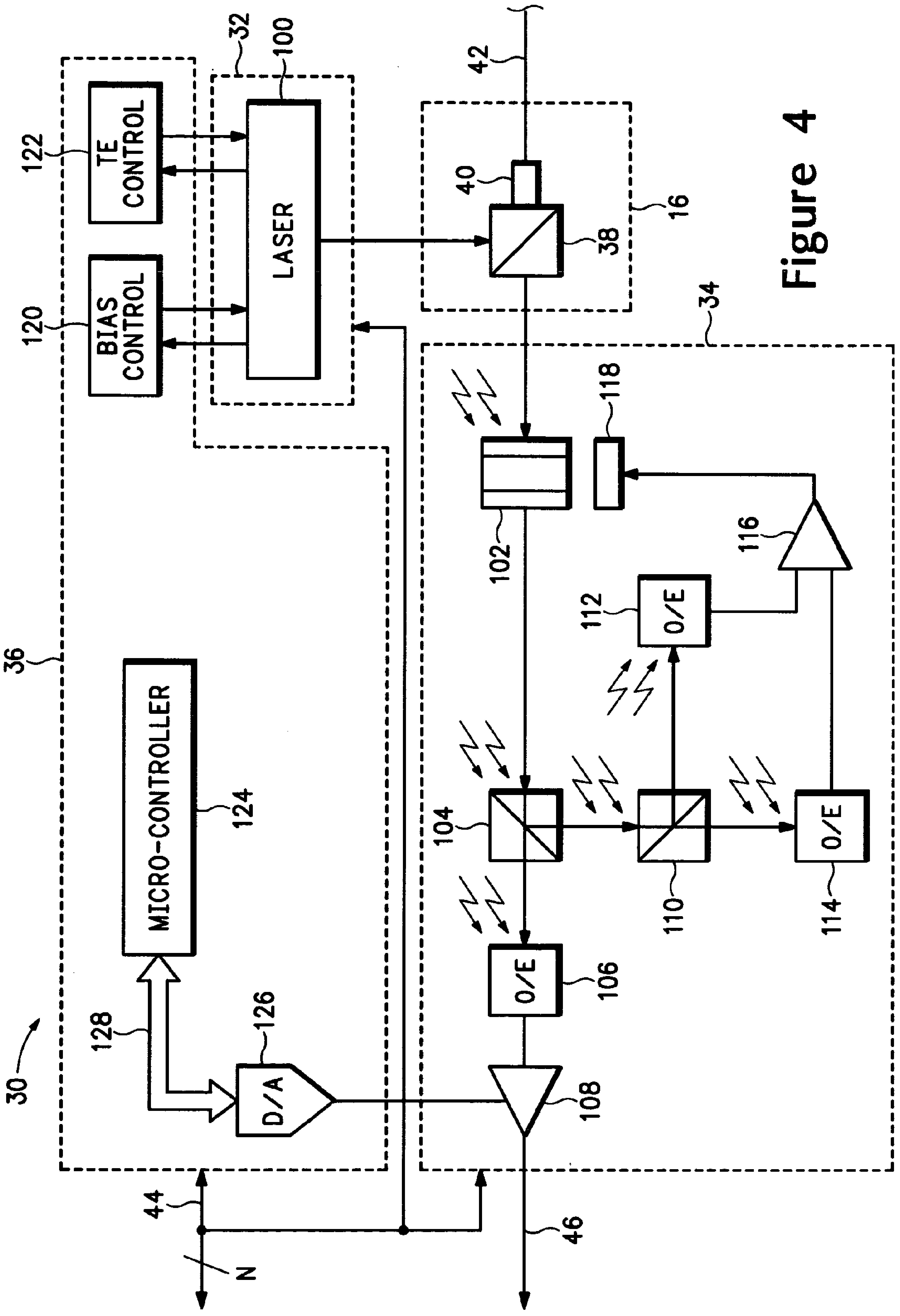
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Figure 4

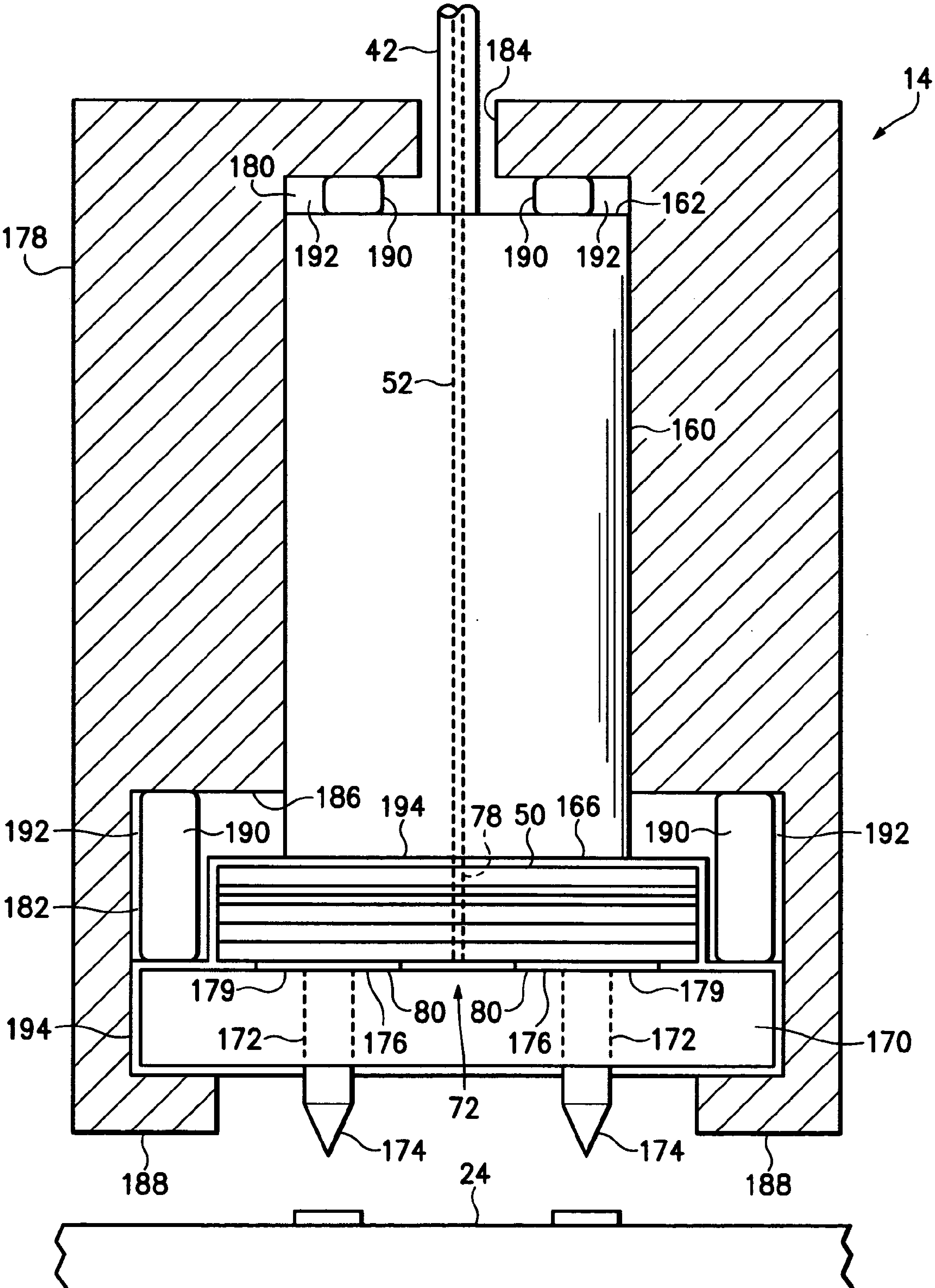
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Figure 5

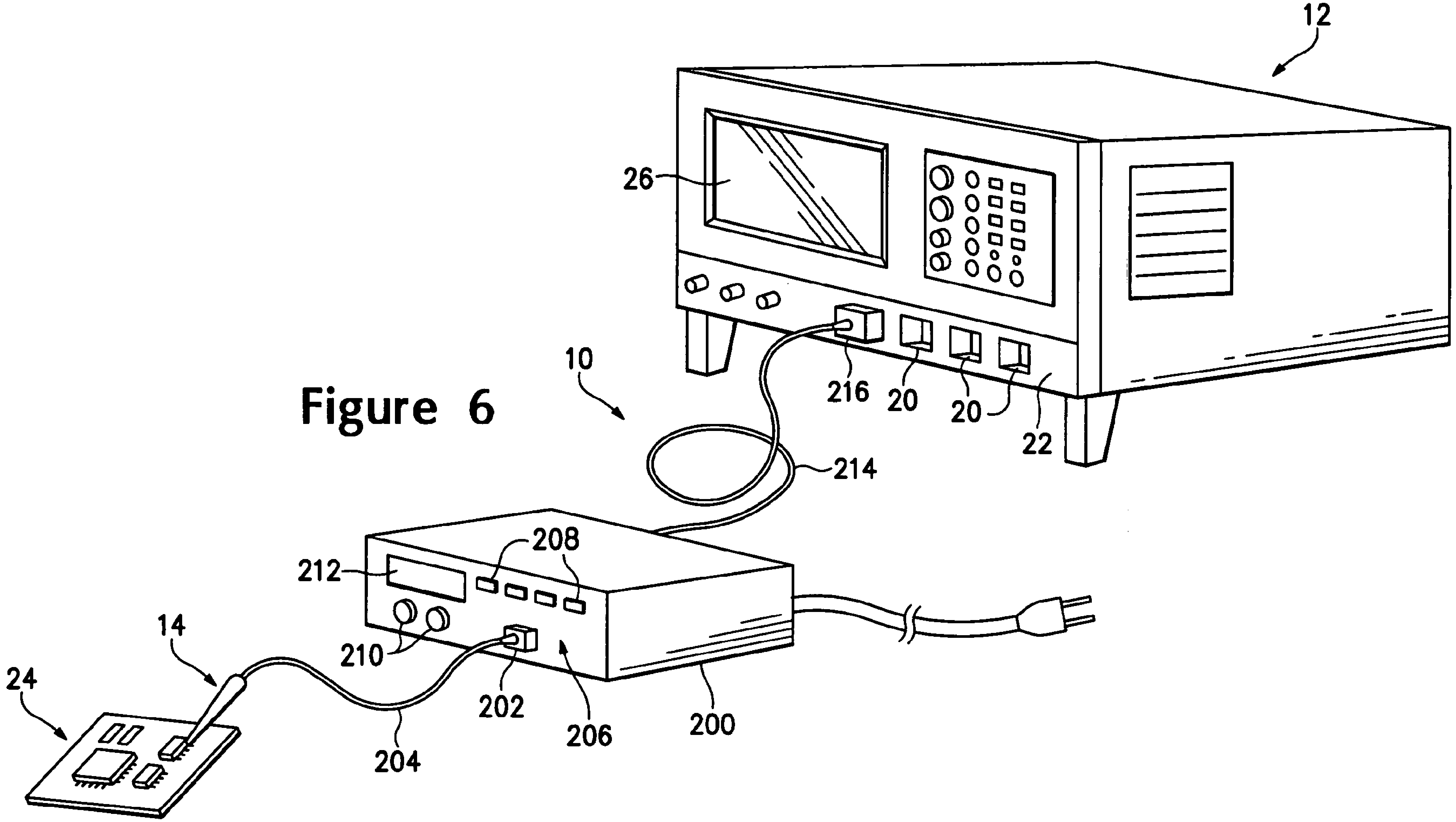

Figure 6

SIGNAL ACQUISITION PROBING SYSTEM USING A MICRO-CAVITY LASER CAPABLE OF SENSING DC VOLTAGES

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of the U.S. Provisional Application No. 60/552,334, filed Mar. 10, 2004.

BACKGROUND OF THE INVENTION

The present invention relates generally to signal acquisition probes and more particularly to signal acquisition probing systems using a micro-cavity laser capable of sensing DC voltages.

U.S. Pat. No. 4,982,405 teaches a Q-switched micro-cavity laser having a first resonant cavity consisting of a gain medium disposed between two optically reflective mirrors. A second optical resonant cavity is formed by two partially reflective mirrors and is physically and optically coupled to the first resonant cavity. The first resonant cavity will lase when pumped by an external optical source. The reflectivity of the intermediate mirror common to the first and second cavities as seen by the gain medium of the first resonant cavity looking toward the second resonant cavity is determined by the resonant modes of the second resonant cavity. It is therefore possible to prevent or permit the gain medium to lase by adjusting the second resonant cavity such that the resonances of the second cavity causes either low reflectivity of the common mirror, which prevents lasing, or high reflectivity in the common mirror, which induces lasing.

The ’405 patent teaches a number of embodiments for varying the second resonant cavity. Of particular interest to the present invention, the second resonant cavity of formed of an electro-optic material disposed between the two partially reflective mirrors with two opposing electrodes disposed adjacent to the electro-optic material. Applying an electric field across the electro-optic material changes the index of refraction of the material, which varies the reflectivity of the intermediate mirror as seem by the gain medium in the gain cavity. This results in the micro-cavity laser generating a train of optical pulses that are dependent on the applied electrical field across the electro-optic material. The ’405 patent also teaches that the second resonant cavity need not affect the gain cavity so much that the lasing is turned on or off. Instead, the resonant cavity can be used to modulate the intensity of the light produced by the gain medium.

A paper titled “Rapidly Tunable Millimeter-Wave Optical Transmitter for Lidar-Radar” by Y. Li, A. J. C. Vieira, S. M. Goldwasser and P. R. Herczfeld teaches the use of two electro-optical mono-mode micro-chip laser sections formed on a single composite crystal for producing a rapidly tunable millimeter wave optical transmitter. The side-by-side micro-chip lasers are formed with a Nd:YVO_4 gain medium resonant cavity and a MgO:$LiNbO_3$ electro-optic resonant cavity. The micro-chip lasers are optically pumped by independent 808 nm high power laser diodes. Electrodes are deposited on opposing sides of each of the electro-optic resonant cavities. A DC voltage is applied to one of the electrodes of one of the electro-optic resonant cavities, which changes the wavelength of the optical output with respect to the other micro-chip laser. The optical output of the micro-chip lasers are heterodyned resulting a tunable beat frequency range of 45 GHz with a voltage sensitivity of 10.6 MHz/V. The transmitter was set at an 8 GHZ bias point using a phase lock loop. A 10 MHZ, 18V peak-to-peak ramp signal is applied to one of the micro-chip lasers. The signal was recovered and measured, which showed a frequency excursion of 190.8 MHz over a 50 ns time corresponding to a chirp rate of 3816 THz/sec. The reference concludes by indicating continuing efforts to increase the voltage sensitivity by reducing the crystal thickness and improving the electrical contacts.

The strength of the electric field distribution within the electro-optic material is a function of the distance between the opposing electrodes and the amplitude of the applied electrical signal. The strength of the electric field is the inverse of the distance separation of the electrodes. As the distance between the electrodes decreases, the strength of the electric field between them increases. As the distance decreases, the magnitude of the electrical signal can decrease to generate the same amount of change in the index of refraction.

Currently, the minimum overall dimensions of the electro-optic material used in optical devices and cavities is limited by the practical size at which the material can be handled resulting in electrodes that are positioned at a substantial distance from the optical path of the optical signal. This results in optical devices having low sensitivity to the applied electrical signal.

There is an increasing need in the electronics industry for measurement test equipment, such as oscilloscopes, logic analyzers and the like, to measure electrical signals in the gigahertz range. Correspondingly, there is a need for measurement instrument signal acquisition probes that have the signal bandwidth to acquire such high frequency signals. Generally gigahertz bandwidth signal acquisition probes have active circuitry in the probing head of the probe that receives the electrical signal via a metal probing tip extending from the end of the probing head. Extensive design work is required to minimize probe tip inductance and capacitance that affect the overall bandwidth of the probe. In addition, the dielectric constant of the probe head material also needs to be minimized for gigahertz differential signal acquisition probes. A further complication for gigahertz signal acquisition probe designs is the signal loss through the coaxial cable that couples the probing head to the measurement instrument.

U.S. Pat. No. 5,808,473, titled “Electric Signal Measurement Apparatus Using Electro-Optic Sampling by One Point Contact” describes an electro-optic sampling high-impedance probe exploiting the Pockels effect to rotate the polarization state of a light beam. The Pockels effect changes the birefringence of an electro-optic crystal by an amount that is proportional to an electric field inside the crystal. With the proper application of electrodes to the crystal surface, and their connection to conductive probing tips, the polarization rotation can be made to respond to a voltage on a device under test (DUT). The electro-optic sampling high-impedance probe receives polarization maintained laser pulses via a single mode polarization maintaining fiber. The laser pulses are coupled through bulk optic devices onto an electro-optic element having a reflective film on one end. A metal pin in the end of the signal probe head abuts the reflective film on the electro-optic element. The metal pin couples an electrical signal from a device under test to the electro-optic element which alters the birefringence of the electro-optic element in response to the electrical field of the signal causing the polarization state of the laser beam to change. The laser beam having the changed polarization state is reflected by the reflecting film and coupled through polarization beam splitters which convert the S and P polarized beams into an intensity change. The S and P polarized beams are coupled through respective condensing lenses onto respective slow germanium photodetectors that convert the optical beams into electrical signals. The electrical signals are coupled to a measurement instrument and detected by a differential amplifier.

U.S. Pat. No. 6,166,845 describes a modification to the above described electro-optic sampling high-impedance probe. Instead of coupling laser pulses via a single mode polarization maintaining fiber to the probe, a laser diode is incorporated into the probe itself. The laser diode generates a pulsed laser output in response to an input pulse chain from the measurement instrument. The probe contains the bulk optic devices, electro-optic element and photodetectors as previously described. The metal pin couples the electrical signal from a device under test to the electro-optic element which alters the birefringence of the electro-optic element in response to the electrical field of the signal causing the polarization state of the laser beam to change. The S and P polarized beams are coupled through the beam splitters and the condensing lenses onto the photodetectors. The photodetectors convert the intensity beams into electrical signals and couple the electrical signals to the measurement instrument.

A drawback to this type of probe is the size of the probing head due to the number of optical elements contained therein. Further, voltage and signal lines are required to couple the voltage power to the laser diode and photodetectors, couple the drive signal to the laser diode and to couple the outputs of the photodetectors to the measurement instrument.

U.S. Pat. No. 5,353,262 describes an ultrasound optical transducer that generates an optical signal the frequency of which varies in correspondence with acoustic energy incident on the transducer. The transducer includes a housing in which is disposed a signal laser. The signal laser is preferably a microchip laser, microcavity laser or the like. The signal laser has an optical cavity disposed between first and second reflectors and in which a lazing medium (also known as a gain crystal) is disposed. The reflectors are disposed on opposing plane-parallel surfaces of the lasing medium. An optical source injects an optical signal at a first frequency into the signal laser, which generates a second output signal at a second frequency. Acoustic energy impinging on the transducer causes the index of refraction of the optical cavity to change which in turn, causes the frequency of the signal laser to change. The frequency modulated optical signal from the signal laser is coupled to signal processing assembly that generates an output signal corresponding to the amplitude of the incident acoustic energy for use in imaging and analysis. An alternative embodiment is described where a piezoelectric device is positioned on the transducer for converting the acoustic energy into an electrical signal. The electrical signal is applied to electrodes on the signal laser. The electrical signal causes a change in the index of refraction of the optical cavity as a function of the acoustic energy applied to the piezoelectric device.

U.S. Pat. No. 5,590,090 describes an ultrasound optical transducer that generates an optical signal the frequency of which varies in correspondence with acoustic energy incident on the transducer. The transducer incorporates an electrically pumped vertical cavity surface emitting laser (VCSEL) array. The cavity length of each laser or pixel of the array is modulated by the acoustic field at the point where the acoustic field contacts the pixels. The resulting laser output is frequency modulated by the acoustic field. The modulation is converted into amplitude modulation at the detector head and then wither detected with a charged couple device (CCD) array with the information being electrically communicated to a signal processing assembly or sent directly by optical fiber to the signal processing assembly.

What is needed is a signal acquisition probing system using a micro-cavity laser that senses DC voltages. The micro-cavity laser used in the signal acquisition probing system needs to provide greater sensitivity to an applied electrical signal to allow measurement small voltage signals.

SUMMARY OF THE INVENTION

Accordingly, the present invention is a signal acquisition probing system for sensing an electrical signal from a device under test. The signal acquisition probing system has an optical transmitter generating a coherent optical signal that is used to optically pump a micro-cavity laser. The micro-cavity laser having an optical gain cavity formed with two vertical cavity surface emitting lasers disposed between opposing optically reflective materials. The optical gain medium and generates first and second polarized optical outputs whose polarization states are orthogonal to each other. The polarized optical outputs from the optical gain medium are coupled to an optical resonant cavity having electro-optic material disposed between opposing optically reflective materials with one of the optically reflective materials being a common reflective material with one of the optical reflective materials of the optical gain cavity. The optical resonant cavity has first and second electrically conductive electrodes receiving the electrical signal from the device under test. Each of the first and second electrically conductive electrodes are formed in at least a portion of the electro-optic material generally parallel to the first and second polarized optical outputs propagating within the electro-optic material. The first and second electrically conductive electrodes are oriented along an axis bisecting the polarization states of the first and second polarized optical outputs. An optical transmission system is optically coupled to the optical transmitter, micro-cavity laser and an optical receiver. The optical transmission system provides the optical signal from the optical transmitter to the micro-cavity laser and provides first and second polarized frequency modulated optical signals to the optical receiver. The first and second polarized frequency modulated optical signals represent the electrical signal from the device under test derived from the device under test electrical signal creating an electromagnetic field distribution in the electro-optic material that overlaps the optical path of the first and second polarized optical outputs propagating in the electro-optic material, which varies the index of refraction of the electro-optic material in the optical path. The optical receiver generates an output electrical signal from the first and second polarized frequency modulated optical signals from the micro-cavity laser.

The electro-optic material in the optical resonant cavity has X, Y, and Z optical axes and corresponding crystal faces orthogonal to the respective X, Y, and Z optical axes. The optically reflective materials may be disposed on the opposing crystal faces orthogonal to one of the X, Y, and Z optical axis. The received optical signal from the optical gain medium propagates generally parallel to at least one of the optical axes in the electro-optic material with the first and second electrically conductive electrodes generally parallel to same optical axis. Electrically conductive contacts may be formed on an exterior surface of the micro-cavity laser that are electrically coupled to one of the electrically conductive electrodes. Additionally, a resistor may be coupled between the electrically conductive electrodes or between the electrically conductive contacts. Further, individual resistors may be electrically coupled to each electrically conductive electrode or the electrically conductive contacts coupled to the electrodes. An acoustic damping material covers a substantial portion of the micro-cavity laser to minimize acoustic modes in the micro-cavity laser.

The optical transmission system has an optical bean splitter coupled to receive the optical signal from the optical transmitter and the polarized frequency modulated optical signals from the micro-cavity laser. A first collimating lens is optical coupled to the beam splitter and a second collimating lens is optically coupled to the micro-cavity laser. A polarization maintaining single mode optical fiber is coupled between the first and second collimating lenses.

The optical receiver has a birefringent etalon optically coupled to receive the polarized frequency modulated optical signals from the micro-cavity laser via the optical beam splitter of the optical transmission system. The birefringent etalon generates polarized intensity modulated optical signals representative of the electrical signal from the device under test. A non-polarizing beam splitter receiving the polarized intensity modulated optical signals and couples a first portion to a first optical-to-electrical converter and a second portion to a polarizing beam splitter. The first optical-to-electrical converter generates an electrical signal representative of the electrical signal under test. The electrical signal from the first optical-to-electrical converter is coupled to an amplifier that generates an amplified electrical signal representative of the electrical signal from the device under test. The polarizing bean splitter couples one of the polarized intensity modulated optical signals to a second optical-to-electrical converter and the other polarized intensity modulated optical signal to a third optical-to-electrical converter. Each of the second and third optical-to-electrical converters generates an electrical signal representative of one of the respective polarized intensity modulated optical signals. An amplifier circuit receives the electrical signals from the second and third optical-to-electrical converters and generates an electrical signal representative of the difference over the sum of the electrical signals from the second and third optical-to-electrical converters. The electrical signal from the amplifier circuit is coupled to a tilt control that is coupled to the birefringent etalon. The tilt control tunes the birefringent etalon to maintain lock between the birefringent etalon and the micro-cavity laser.

The objects, advantages and novel features of the present invention are apparent from the following detailed description when read in conjunction with appended claims and attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates the signal acquisition probing system according to the present invention.

FIG. **2** general block diagram of the circuitry in the signal acquisition probing system according to the present invention.

FIG. **3** illustrate the micro-cavity laser used in a signal acquisition probing system according to the present invention.

FIG. **4** illustrates more detailed block diagram of the circuitry in the signal acquisition probing system according to the present invention.

FIG. **5** illustrates a partially sectioned view of the probing components within the probing head in the signal acquisition probing system according to the present invention.

FIG. **6** illustrates a further embodiment of the signal acquisition probing system according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. **1**, there is illustrated a signal acquisition probing system **10** coupled to a measurement instrument **12**, such as real-time or sampling oscilloscopes, logic analyzer, vector network analyzer, or the like. The signal acquisition probing system **10** has a probing head **14** containing a micro-cavity laser and an optical transmission system **16** extending from the probing head **14** to a probe interconnect housing **18**. The probe interconnect housing **18** contains signal acquisition probing circuitry needed to provide an optical signal to the probing head **14** and convert returning frequency modulated optical signals to an electrical signal. The optical transmission system **16** includes a polarization maintaining single mode optical fiber. The probe interconnect housing **18** is removably connected to one of several interconnect receptacles **20** on the front panel **22** of the measurement instrument **12**. The probe interconnect housing **18** and interconnect receptacles **20** are preferably TekConnect® interface devices such as described in U.S. Pat. No. 6,402,565 and incorporated herein in its entirety by reference. The TekConnect® interface has connections for coupling a wide bandwidth signal to measurement instrument, providing electrical power from the measurement instrument **12** to the probe interconnect housing **18** and communication signals between the measurement instrument **12** to the probe interconnect housing **18** as described in U.S. Pat. No. 6,629,048 and incorporated herein in its entirety by reference. The electrical signal representing the measured signal from the device under test **24** is coupled to acquisition circuitry within the measurement instrument **12** that converts the electrical signal into digital data values and stores the data values in memory. Processing circuitry operating under program control processes the digital data values to produce display data that is displayed on a display device **26**, such as a liquid crystal display, cathode ray tube or the like. Alternately, the measurement instrument **12** may include the signal acquisition probing circuitry. The probe interconnect housing **18** would then include an optical connector for coupling the optical signal to the probing head **14** and the return frequency modulated optical signals to the measurement instrument **12**.

The below described signal acquisition probing system **10** has the capability to sense DC voltages of a signal under test. The approach is to create two frequency modulated laser signals from a single laser cavity. The two frequencies can be separated at a slope filter. The laser signals are modulated in a complementary fashion by the signal under test. In this way, the outputs of the slope filter can be combined to generate a differential signal that is immune to errors affecting both the laser cavity signals, such as temperature drift, mechanical shock, and the like. The signal acquistion probing system **10** uses two orthogonal linearly polarized states to allow separation of the two laser cavity output frequencies. Circularly polarized orthogonal states could also be used.

FIG. **2** is a general block diagram of the signal acquisition probing circuitry **30** disposed in the probe interconnect housing **18** for a probing head **14** having a micro-cavity laser functioning as a voltage signal sensor. The signal acquisition probing circuitry **30** includes an optical transmitter **32**, optical receiver **34** and control circuitry **36** for the optical transmitter **32** and receiver **34**. The optical output from the optical transmitter **32** and the optical input to the optical receiver **34** are coupled through an dichroic optical beam splitter **38** in the optical transmission system **16**. A collimating lens **40** focuses the optical signal from the beam splitter **38** into a polarization maintaining single mode optical fiber **42**. The polarization maintaining single mode optical fiber **42** couples the optical output of the optical transmitter to the micro-cavity laser in the probing head **14** and couples frequency modulated optical signals from the micro-cavity laser to the beam splitter **38**. Data/control and voltage power lines **44** couple the signal acquisition probing circuitry **30** in the probe interconnect housing **18** to the measurement instrument **12**. A high speed coaxial interconnect **46** couples the electrical signal from the optical receiver **34** to the measurement instrument **12**.

Referring to FIG. **3**, there is shown the a micro-cavity laser **50** disposed in the probing head **14** of the signal acquisition probing system **10**. The micro-cavity laser **50** receives an optical signal **52** from the optical transmitter **32**. The micro-cavity laser **50** has an optical gain cavity **54** implemented with two vertical cavity surface emitting laser (VCSEL) crystals **56** and **58**. The VCSELs are active gain mediums that are disposed between two optically reflective materials **60** and **62**. The VCSEL laser crystals **56** and **58** are of the group of inorganic crystals, such as GaAs, AlGaAs, InGaAsP and the like, that generate a coherent, polarized optical output **64** when either pumped by an coherent optical input, such as the optical signal **52** or by a forward bias voltage on the VCSEL. Alternately, the active gain medium maybe formed of other crystalline materials, such as Neodymium doped Yttrium Orthovanadate (Nd:YVO_4) or the like. An optical resonant cavity **66** is coupled to the optical gain cavity **54** and has an electro-optic material **68** disposed between opposing optical reflective materials **62** and **70** where the optically reflective material **62** is common to the optical gain cavity **54**.

The optically reflective materials **60**, **62** and **70** are preferably ceramic mirrors formed from layers of zirconium dioxide, silicon dioxide and silicon nitride. It is important in certain applications that the optically reflective materials be non-metallic to reduce capacitive and inductive effects. The reflectivity of the optically reflective materials **60**, **62** and **70** vary depending on the proposed application for the micro-cavity laser **50**. The optically reflective materials **60**, **62** and **70** may be partially reflective or totally reflective to particular wavelengths of light. For example, optically reflective material **60** may have low reflectivity for the pump laser light (e.g. 5% reflectivity) of the optical signal **52** and high reflectivity (e.g. 99.5% reflectivity) for the laser light **68** generated by the gain mediums **56** and **58**. The optical reflective material **62** may have high reflectivity for the pump laser light (e.g. greater than 90% reflectivity) and medium reflectivity for the laser light **68** of the VCSEL lasers **56** and **58** (e.g 50% reflectivity). The optically reflective material **70** generally has a high reflectivity (e.g. 95 to 99.5% reflectivity) depending on the output direction of the laser light **64** from the micro-cavity laser **50**. The reflectivity of the optical reflective medium **70** is a high as possible for generating an output along the same path as the pump laser light. The reflectivity of the optically reflective material **70** is as high as 99.5% for generating an output opposite that of the pump laser light.

The VCSELs **56** and **58** produce polarized laser light of a frequency determined by the modes of the micro-cavity laser **50**. Applying an electromagnetic field across the electro-optic material **68** changes the index of refraction of the material, causing the reflectivity of the optically reflective material **68** to vary as seen by the VCSELs **56** and **58** in the optical gain cavity **54**. The application of the varying electromagnetic field results in frequency modulation of the laser light **64** of the VCSELs **56** ans **58** as the reflectivity of the common optically reflective material **22** seen by the VCSELs **56** and **58** changes due to resonances in the optical resonant cavity **66**.

The electro-optical material **68** in the optical resonant cavity **66** may be formed from inorganic crystal material, such as Zinc Telluride (ZnTe), Cadmium Telluride (CaTe), Zinc Selenide (ZnSe), Gallium Arsenide (GaAs), Indium Phosphide (InP), or other electro-optic materials having a cubic 43 m symmetry and having the property of a changing index of refraction in response to an applied electromagnetic field. The inorganic crystal materials further have X, Y and Z optical axes which coincide with the crystallographic axes.

The optical resonant cavity **66** will be described below in relation to Zinc Telluride (ZnTe) electro-optic material having optical axes coincident with the crystallographic axes. The present invention will be described in relation to specific optical axes of the Zinc Telluride electro-optic material **68** and a specific orientation of a propagating laser light **64** and orientations of the electromagnetic field within the Zinc Telluride electro-optic material **68**. In the preferred embodiment, the Zinc Telluride electro-optic material **68** is an X-cut crystal face where the cleaved and polished surfaces of the crystal are perpendicular to the optical X-axis. Alternatively, the Zinc Telluride electro-optic material **68** may be a Y-cut crystal face. The X-cut crystal is preferred over the Y-cut crystal for minimizing distortions from the acoustic modes generated within the electro-optic material **68**.

The micro-cavity laser **50** has an electrode structures **72** formed in the optical resonant cavity using well known semiconductor manufacturing processes. The electrode structure **72** has electrically conductive electrodes **74** and **76** formed in the optically reflective material **70** and the Zinc Telluride electro-optic material **68** that are generally parallel to the optical path **78** of the laser light **64** from the optical gain cavity **54** propagating through the electro-optic material **68**. The electrically conductive electrodes **74** and **76** are formed in the electro-optical material parallel to the principle dielectric axis of the electro-optical material **68** that provides the largest changes in the index of refraction for an applied electro-magnetic field. The electrically conductive electrodes **74** and **76** are disposed on the opposite sides of the optical path **78** of the propagating laser light **64**. The electrically conductive electrodes **74** and **76** are preferably formed as close as possible to the optical path **78** of the propagating laser light **64** with the electrode separation, for example, being in the range of 45 to 120 microns. In some applications, the electrically conductive electrodes **74** and **76** may extend into the optical path **78** of the propagating laser signal **64**. The electrically conductive electrodes **74** and **76** have a polygonal sectional shape with an apex directed toward the optical path **78** of the propagating laser signal **64**. The apexes of the polygonal shapes concentrates the electromagnetic field across the optical path **78**. Alternately, the electrically conductive electrodes **76** and **78** maybe circular in form. Electrically conductive contacts **80** maybe formed on the exterior surface **82** of the micro-cavity laser **50** using well know deposition techniques, such as thin and thick film processes. The electrically conductive contacts **80** are preferably formed of gold deposited over a layer of chromium. Each of the electrically conductive contacts **80** is preferably a polygonal shape with an apex electrically coupled to one of the electrically conductive electrodes **74** and **76**. In the embodiment where the electrically conductive electrodes are circular, the separation between the electrically conductive contacts **80** is in the range of 15 to 100 microns with the electrically conductive electrodes **74** and **76** set slightly back from the apexes of the contacts **80**.

The described electrode structure **72** has an high input impedance. In certain applications it may be preferable to match the impedance of the electrode structure **72** to the impedance of the device under test **24**. An optional termination resistor **84** is shown formed on exterior surface **82** of the micro-cavity laser **50**. The termination resistor **84** is connected between the electrically conductive electrodes **74** and **76** of the optical resonant cavity **66**. The termination resistor **84** may be formed using well known processing techniques, such as thin or thick film processing. The resistance of the termination resistor **84** is set to match the impedance of the electrical device driving the optical resonant cavity **66**.

The VCSELs **56** and **58** are oriented with their polarization axes at right angles to each other as represented by the mutually perpendicular axes PA_1 and PA_2. The pumped laser light **52** from the optical transmitter **32** is partially absorbed by the first VCSEL **56** and continues to be absorbed by the second VCSEL **58**. This combination lases simultaneously in two polarization states. The length of the VCSELs **56** and **58** are selected so that equal amounts of pump laser light **52** are absorbed in both VCSELs **56** and **58**. The polarization states of the two lasing modes are selected to be +45° and −45° to the principle dielectric Z-axis of the electro-optic material **68** in the optical resonant cavity **66**. The two polarization states see equal but opposite frequency modulation through the Pockels effect in the electro-optic material **68**. Frequency modulation due to temperature changes in the micro-cavity laser **50** are common-mode to both polariztion states.

FIG. **4** is a more detailed block diagram of the signal acquisition probing circuitry **30** in the probe interconnect housing **18**. The optical transmitter **32** is preferably a laser diode **100** generating an optical output having a wavelength in the range of 600 to 1500 nm. The laser diode **100** includes a thermoelectric (TE) cooler and thermistor for controlling the wavelength of the laser output and a photodetector for generating an electrical output representative of the magnitude of the laser output. The optical receiver **34** has a birefringent etalon **102** acting as a slope filter receiving the frequency modulated optical signals from the beam splitter **38**. The birefringent etalon **102** is composed of an optical wave-plate. The two polarization states returning along the polarization maintaining optical fiber **42** are aligned with the principle axes of the wave-plate. Each polarization state sees a separate etalon transmission curve. The birefirgent etalon **102** converts the frequency modulated optical signals into polarized intensity modulated optical signals, which are coupled though a non-polarizing bean splitter **104**. A substantial portion of the polarized intensity modulated optical signals is coupled through the beam splitter **104** and superimposed on a high-speed optical-to-electrical converter (O/E) **106**, such as a PIN or avalanche photodiode. The O/E converter **106** converts the superimposed intensity modulated optical signals to an amplitude modulated electrical signal representative of the signal being measured on the device under test **14**. The electrical signal from the O/E converter **106** is amplified by amplifier circuitry **108** and coupled via the coaxial interconnect **46** to the measurement instrument **12**. The remaining portion of the polarized intensity modulated optical signal from the beam splitter **104** is coupled to a polarizing bean splitter **110**. The polarizing beam splitter **110** couples one of the polarized intensity modulated optical signals to a first slow detector **112** and the other polarized intensity modulated optical signal to a second slow detector **114**. The first and second slow detectors are preferably optical-to electrical converters implemented as a phtodiode. The output of the first and second slow detectors **112** and **114** are provided to a amplifier circuit **116**, which is preferably a delta sigma amplifier. The output of the amplifier circuit **116** is the difference over the sum of the two detector signal and provides a feedback signal to a tilt control **118** for the etalon **102**. The tilt control **118** tunes the etalon **102** so that the frequencies of both polarization states coincide with the intersection point of the two etalon transmission curves near a transmission of 0.55 to maintain lock between the etalon **102** and the micro-cavity laser **50**. The tilt control **118** may be mechanical, electrical or thermal.

The control circuitry **36** includes bias and thermo-electric (TE) control circuitry **120** and **122** for maintaining the laser output at a constant level and at an optimum wavelength. The bias control circuitry **120** provides a feedback loop to maintain the optical output of the laser **100** at a constant level. The laser **100** includes a photodetector who current output is coupled to the inverting input of a positive gain drive amplifier. The non-inverting input of the drive amplifier is coupled to a reference voltage. As the output of the photodetector increases and decreases with changes in the output power of the laser **100**, the signal applied to the inverting input of the drive amplifier varies the output of the drive amplifier. The drive amplifier varies the bias on the laser **100** to maintain the laser output at a constant level.

The TE control circuitry **122** provides a feedback loop to maintain the optical output of the laser **100** at a predetermined wavelength. The laser **100** package includes a thermo-electric cooler and a thermistor. The output of the thermistor varies in response to temperature changes of the laser **100**. The thermistor output is coupled to inverting input of a TE cooler drive amplifier. The non-inverting input of the drive amplifier is coupled to a reference source. The TE control circuitry **122** is designed to produce the equal voltages on the inverting and non-inverting inputs of the TE cooler drive amplifier when the laser **100** generates the optimum output laser wavelength. Changes in the output of the thermistor causes the voltage to the inverting input of the TE drive amplifier to increase or decrease causing the output voltage of the TE drive amplifier to change. The output of the TE drive amplifier is applied to the TE cooler in the laser **100** which causes the wavelength of the laser **100** to increase or decrease accordingly.

The control circuitry **36** also includes a micro-controller **124** that communicates with the measurement instrument **12** via data/control and voltage lines **44**. The data/control and voltage lines **44** also provides electrical power to the optical transmitter and receiver and control circuitry **32**, **34**, **36**. The micro-controller **124** is shown coupled a digital-to-analog converter (D/A) **126** via the data and control bus **128** for controlling the gain of the amplifier circuitry **108**. Additional electronically controlled circuitry, such as variable attenuators, gain cells and the like, may be incorporated into the output signal path of the optical receiver **34**.

FIG. **5** is a partially sectioned view illustrating the probing components within the probing head **14**. The probing components include a collimating lens **160** having a top flat surface **162** which receives the polarization maintaining optical fiber. The micro-cavity laser **50** is secured to the opposing bottom surface **166** of the collimating lens using a non-conductive adhesive, such as epoxy or the like. The preferred structure of the micro-cavity laser **50** is essentially the same as previously described. The micro-cavity laser **50** has the electrode structure **72** with electrically conductive contacts **80** formed on the bottom exterior surface of the micro-cavity laser **50**. The reflective coating **60**, **62** and **70** that form parts of the micro-cavity laser **50** are formed of the previously described non-conductive materials. It is important in probing applications to minimize conductive materials near the micro-cavity laser **50** to limit inductive and capacitive interference in the operation of the micro-cavity laser. The micro-cavity laser **50** has a preferred length and width of 1 mm and a thickness along the optical X-axis of approximately 20 microns. The optics in the collimating lens **160** produces a collimated beam **52** from the optical fiber **42** that is focused along an optical path **78** substantially parallel to the electrode structure **72** in the micro-cavity laser **50**. The frequency modulated optical signals generated within the micro-cavity laser **50** exits through the reflective coating **60** and passes through the collimating lens **160**, which focuses the frequency modulated optical signal on the optical fiber **42**.

Disposed adjacent to the bottom surface of the micro-cavity laser **50** is a probe contact substrate **170** for supporting probing contacts, such as contact pads and probing tips. The probe contact substrate **170** is preferably formed of a non-conductive material, such as alumina, circuit board material or the like. In one embodiment, the probe contact substrate **170** has apertures **172** formed therein for receiving electrically conductive probing tips **174**. The electrically conductive probing tips **174** are electrically coupled to the electrically conductive contacts **80** on the micro-cavity laser **50**. The electrically conductive probing tips **174** may directly contact the electrically conductive contacts **80** but it is preferable that electrically conductive contacts **176** be formed on the upper surface of the probe contact substrate **170** that are electrically coupled to the probing tips **174**. The electrically conductive contacts **176** on the probe contact substrate **170** electrically contact the electrically conductive contacts **80** on the micro-cavity laser **50**. A conductive adhesive, such as epoxy or the like, is applied to the contacts **80** and **176** for securing the probe contact substrate **170** to the micro-cavity laser **50**. Alternately, flexible type electrical contacts be disposed between the probing pins **174** and the contacts **80**. The flexible type contacts may take the form of electrically conductive elastomers, flexible C-type string contacts, or the like. A mechanical registration element would attach the probe contact substrate **170** to the micro-cavity laser **50**. In a further embodiment, the apertures **172** and probing tips **174** may be replaced with protrusions extending from the bottom of the probe contact substrate **170** forming the probing contacts. Electrically conductive material, such as gold plated over a layer of chromium, is disposed on the bottom surfaces of the protrusions. Electrically conductive vias are formed in the probe contact substrate **170** to electrically couple the electrically conductive contacts on the protrusions to the top surface of the substrate **170**.

Optical cavities used as voltage sensing devices, such as the micro-cavity laser **50**, are high impedance devices. In certain probing applications it may be preferable to match the impedance at the probe to the impedance of the device under test **24**. As previously described in relation to FIG. **3**, the optional termination resistor **84** may be connected between the electrically conductive electrodes **74** and **76** of the electrode structure **72** or between the electrically conductive contacts **80** on the exterior surface **82** of the micro-cavity laser **50**. The resistance of the termination resistor **84** is set to match the impedance of the device under test **24**. This allows differential measurements to be made in a defined impedance environment, such as 50 ohms. Terminating the sensing device in the impedance of the device under test improves signal fidelity by reducing the reflections that would be caused by impedance mismatches between the device under test and the sensing device. The resistance of the termination resistor **84** may be set to various values to conform to specific device under test impedance environments. In addition, damping resistors **179** may be formed on the exterior surface of the micro-cavity laser **50** and coupled in series with each of the electrically conductive electrodes of the electrode structure **72**. The damping resistors **179** may also be formed on the probe contact substrate **170** in series with the electrically conductive contacts **176** formed on the upper surface of the probe contact substrate **170**.

The collimating lens **160**, the micro-cavity laser **50** and the probing contact substrate **170** are disposed within a non-conductive housing **178**, formed from ABS plastic, poly-carbonate, poly-carbonate ABS, poly-phenylene sulfide or the like. The housing has a first cavity **180** for receiving the collimating lens **160** and a second cavity **182** for receiving the micro-cavity laser **50** and the probe contact substrate **170**. The housing has an opening **184** extending from the top surface of the housing to the first cavity **180** to allow the optical fiber **42** to be connected to the collimating lens **160**. The interface between the first and second cavities **180** and **182** defines a shoulder **186**. A rib **188** is formed at the bottom of the housing **178** that protrudes into the second cavity **182** for supporting the probe contact substrate **170**, the micro-cavity laser **50** and the collimating lens **160**. The first and second cavities **180** and **182** are sized to closely conform to the lateral dimensions of the collimating lens **160** and the probe contact substrate **170**. Both cavities **180** and **182** are sized to provide excess vertical clearance for the collimating lens **160** and the probe contact substrate **170** so as to provide axial movement of the probing elements within the housing **178**. A spring mechanism **190**, in the form of elastomeric material, mechanical springs or the like, is provided in the gaps **192** between the housing **178** and the collimating lens **160** and the probe contact substrate **170**. The housing **178** is disposed within a probing head shell that provides strain relief for the optical fiber **42** and protection and support for the elements within the housing **178**.

An acoustic damping material **194** may be applied to substantially all of the surfaces of the micro-cavity laser **50** leaving gaps for the optical signals leaving and entering the collimating lens **160** and for the electrical connections between the electrically conductive contacts **80** on the micro-cavity laser **50** and the electrically conductive contacts **176** on the probe contact substrate **170**. In the preferred implementation, the acoustic damping material **194** is applied to substantially all of the outer exposed surfaces of the micro-cavity laser **50** and the probe contact substrate **170**. A gap is provided on the top surface of the micro-cavity laser **50** for the optical signals leaving and entering the collimating lens **160** and the probing contacts **174** extending from the bottom of the probe contact substrate **170** are left exposed.

The probe interconnect housing **18** is plugged into one of the interconnect receptacles **20** in the measurement instrument **12**. Parameters may be set for the signal acquisition probing system **10**, such as gain or attenuations levels of the optical receiver or the like, using controls on the measurement instrument **12** or via commands sent to the measurement instrument **12** via an external communications bus.

The optical transmitter **32** in the signal acquisition probing circuitry **30** generates an optical output that is coupled via the polarization maintaining single mode optical fiber **42** in the optical transmission system **16** to the bulk optic collimating lens **160**. The collimating lens **160** focuses the optical signal on the micro-cavity laser **50**. The user contacts the probing head **14** to a selected test node on the device under test **24** to acquire a signal to be measured. The measured signal may be a differential signal or a single signal. The measured signal is coupled through the probing contacts or pins **174** of the probe contact substrate **170** to the electrode structure **72** in the micro-cavity laser **50**. The electrical signal on the electrode structure **72** varies the index of refraction of the electro-optic material **68** in the micro-cavity laser **50** as a function of the magnitude changes in the electric signal. The changing index of refraction in the electro-optic material **68** causes corresponding changes in the wavelength of the laser signals in the micro-cavity laser **50**. The frequency modulated optical signals pass out of the micro-cavity laser **50** into the collimating lens **160** which focuses the frequency modulated optical signals onto the end of the optical fiber **42**. The optical fiber **42** couples the frequency modulated optical signal to the beam splitter **38**. The beam splitter **38** coupled the frequency modulated optical signals to the birefringent etalon **102** in the optical receiver **34** of the signal acquisition probing circuitry **30**. The birefringent etalon **102** converts the frequency modulated optical signals into polarized intensity modulated optical signals that are coupled to the nonpolarizing beam splitter **104**. The nonpolarizing beam splitter **104** superimposes a substantial portion of the polarized intensity modulated optical signals to the O/E converter **106**. The O/E converter **106** converts the polarized intensity modulated optical signals into an electrical signal representative of signal being measured on the device under test **24**. The electrical output from the O/E converter **106** is amplified in the amplifier circuitry **108** and coupled to the measurement instrument **12** via the high speed coaxial interconnect **46**. The remaining potion of the polarized intensity modulated optical signals from the beam splitter **104** coupled through a polarizing beam splitter **110**. The polarizing beam splitter **110** couples one of the polarized intensity optical signals to a first slow detector **112** and the other polarized intensity modulated optical signal to a second slow detector **114**. The outputs of the first and second slow detectors **112** and **114** are provided to a amplifier circuit **116**, which provides a feedback signal to a tilt control **118** for the etalon **102**. The tilt control **118** tunes the etalon **102** to maintain lock between the etalon **102** and the micro-cavity laser **50**.

FIG. **6** illustrates a further embodiment of the signal acquisition probing system **10** for probing electrical signal on a device under test **24**. The probe interconnect housing **18** is replaced with an independently powered probe controller **200** and an interconnect adapter **216**. The probe controller **200** contains the optical transmitter **32** that provides the optical signal to the probe head **14** and the optical receiver **34** that converts the returning frequency modulated optical signals to an electrical signal. The probe controller **200** also includes associated processing circuitry, such as a microcontroller, memory, ASICs and the like, and a power supply for generating the necessary voltages for operating the circuitry within the controller **200**. The probe controller **200** includes at least a first optical connector **202** for coupling optical signals to and from the probing head **14**. The probe controller **200** may include front panel controls **206**, such as switches **208**, knobs **210** and a display **212** to allow for operator inputs to the controller **200**. A electrical output connector is provided for coupling a wide bandwidth coaxial cable **214** having wide bandwidth connectors, such as SMA connectors, from the probe controller **200** to the measurement instrument **12**. The interconnect adapter **216**, such as described in U.S. Pat. No. 6,402,549 and incorporated herein in its entirety by reference, includes a corresponding wide bandwidth connector. The interconnect adapter **216** may be modified to include signal lines for allowing communications between the measurement instrument **12** and the probe controller **200**.

A signal acquisition probing system has been described where micro-cavity laser is used to acquire an electrical signal from a device under test. The micro-cavity laser has first and second VCSEL gain mediums and an electro-optic optical resonant cavity. The micro-cavity laser is pumped by an external laser source with each VCSEL generating a polarized laser output that is coupled to the optical resonant cavity. The polarization states of VCSELs' polarized laser are at 90° to each other. The micro-cavity laser generates respective polarized frequency modulated optical signals derived from the device under test electrical signal creating an electro-magnetic field distribution in electro-optic material in the micro-cavity laser that overlaps the optical path of the optical signal propagating in the electro-optic material. The electromagnetic field varies the index of refraction of the electro-optic material in the optical path. The frequency modulated optical signals are coupled to an optical receiver via the optical transmission system which converts the frequency modulated optical signals to an electrical signal. The electrical signal is coupled to measurement test instrument for processing and displaying of the electrical signal. The signal acquisition probing system included control circuitry for controlling the optical power level and wavelength of the optical signal from the optical transmitter and the gain of the output electrical signal from the optical receiver.

It will be obvious to those having skill in the art that many changes may be made to the details of the above-described embodiments of this invention without departing from the underlying principles thereof. The scope of the present invention should, therefore, be determined only by the following claims.

What is claimed is:

1. A signal acquisition probing system using electro-optic detection for sensing an electrical signal from a device under test comprising:

an optical transmitter generating a coherent optical signal;

a micro-cavity laser having an optical gain cavity formed with two vertical cavity surface emitting lasers disposed between opposing optically reflective materials that receives the optical signal from the optical transmitter and generates first and second polarized optical outputs whose polarization states are orthogonal to each other, and an optical resonant cavity having electro-optic material disposed between opposing optically reflective materials with one of the optically reflective materials being a common reflective material with one of the optical reflective materials of the optical gain cavity that receives the first and second polarized optical outputs from the optical gain cavity;

first and second electrically conductive electrodes receiving the electrical signal from the device under test with each of the first and second electrically conductive electrodes being formed in at least a portion of the electro-optic material generally parallel to the first and second polarized optical outputs propagating within the electro-optic material, the first and second electrically conductive electrodes being oriented along an axis bisecting the polarization states of the first and second polarized optical outputs;

an optical transmission system optically coupled to the optical transmitter, micro-cavity laser and an optical receiver providing the optical signal from the optical transmitter to the micro-cavity laser and providing first and second polarized frequency modulated optical signals to the optical receiver representing the electrical signal from the device under test derived from the device under test electrical signal creating an electromagnetic field distribution in the electro-optic material that overlaps the optical path of the first and second polarized optical outputs propagating in the electro-optic material, which varies the index of refraction of the electro-optic material in the optical path; and

the optical receiver generating an output electrical signal from the first and second polarized frequency modulated optical signals from the micro-cavity laser.

2. The signal acquisition probing system as recited in claim **1** further comprising a resistor coupled between the first and second electrically conductive electrodes.

3. The signal acquisition probing system as recited in claim **1** further comprising a resistor coupled to each of the first and second electrically conductive electrodes.

4. The signal acquisition probing system as recited in claim **1** wherein the micro-cavity laser further comprises electrically conductive contacts formed on an exterior surface of the micro-cavity laser with the one of the electrically conductive contacts electrically coupled to the first electrically conductive electrode and the other electrically conductive contact electrically coupled to the second electrically conductive electrode.

5. The signal acquisition probing system as recited in claim **4** further comprising a resistor coupled between the electrically conductive contacts.

6. The signal acquisition probing system as recited in claim **4** further comprising a resistor coupled to each of the electrically conductive contacts.

7. The signal acquisition probing system as recited in claim **1** wherein the first and second polarized optical output from the optical gain cavity propagates generally parallel to at least a first optical axis in the electro-optic material with the first and second electrically conductive electrodes generally parallel to same optical axis.

8. The signal acquisition probing system as recited in claim **1** wherein the electro-optic material has X, Y, and Z optical axes and corresponding crystal faces orthogonal to the respective X, Y, and Z optical axes with the optical resonant cavity further comprising the opposing optically reflective materials being disposed on the Y-crystal face and the first and second electrically conductive electrodes being orthogonal to the Y-crystal face of the electro-optic material.

9. The signal acquisition probing system as recited in claim **1** wherein the electro-optic material has X, Y, and Z optical axes and corresponding crystal faces orthogonal to the respective X, Y, and Z optical axes with the optical resonant cavity further comprising the opposing optically reflective materials being disposed on the X-crystal face and the first and second electrically conductive electrodes being orthogonal to the X-crystal face of the electro-optic material.

10. The signal acquisition probing system as recited in claim **1** wherein the electro-optic material has X, Y, and Z optical axes and corresponding crystal faces orthogonal to the respective X, Y, and Z optical axes with the optical resonant cavity further comprising the opposing optically reflective materials being disposed on the Z-crystal face and the first and second electrically conductive electrodes being orthogonal to the Z-crystal face of the electro-optic material.

11. The signal acquisition probing system as recited in claim **1** wherein the optical transmission system further comprises an optical bean splitter coupled to receive the optical signal from the optical transmitter and the polarized frequency modulated optical signals from the micro-cavity laser, first and second collimating lenses with the first collimating lens optically coupled to the optical beam splitter and the second collimating lens optically coupled to the micro-cavity laser and a polarization maintaining single mode optical fiber coupled between the first and second collimating lenses.

12. The signal acquisition probing system as recited in claim **11** wherein the optical receiver further comprises:

a birefringent etalon optically coupled to receive the polarized frequency modulated optical signals from the micro-cavity laser via the optical beam splitter of the optical transmission system, and generating polarized intensity modulated optical signals representative of the electrical signal from the device under test;

a non-polarizing beam splitter receiving the polarized intensity modulated optical signals and coupling a first portion to a first optical-to-electrical converter and coupling a second portion to a polarizing beam splitter, with the first optical-to-electrical converter generating an electrical signal representative of the electrical signal under test;

an amplifier coupled to receive the electrical signal from the first optical-to-electrical converter and generating an amplified electrical signal representative of the electrical signal from the device under test;

a second optical-to-electrical converter coupled to receive one of the polarized intensity modulated optical signal from the polarizing beam splitter and a third optical-to-electrical converter coupled to receive the other polarized intensity modulated optical signal from the polarizing beam-splitter; with each of the second and third optical-to-electrical converters generating an electrical signal representative of one of the respective polarized intensity modulated optical signals;

an amplifier circuit receiving the electrical signals from the second and third optical-to-electrical converters and generating an electrical signal representative of the difference over the sum of the electrical signals from the second and third optical-to-electrical converters; and

a tilt control coupled to the birefringent etalon receiving the electrical signal from the amplifier circuit for tuning the birefringent etalon to maintain lock between the birefringent etalon and the micro-cavity laser.

13. The signal acquisition probing system as recited in claim **1** further comprising an acoustic damping material substantially covering the micro-cavity laser to minimize acoustic modes in the micro-cavity laser.

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